Testing Soils and Cornstalks to Evaluate Nitrogen Management on the Watershed Scale

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ABSTRACT

High nitrate (NO_3–N) concentrations in Iowa rivers have been linked to areas of intensive row crop production, but they have not been experimentally linked to specific management practices used during row crop production. This study demonstrates how the late-spring test for soil NO_3–N and the end-of-season test for cornstalk NO_3–N can be used to measure N sufficiency levels across many fields and how the results can be used to evaluate management practices within a watershed. More than 3200 soil and cornstalk samples were collected over a 12-yr period from fields planted to corn (*Zea mays* L.) and already fertilized by farmers using their normal practices. Results showed that early-season rainfall and associated N losses were major factors affecting N concentrations in soils and cornstalks. Evidence for NO_3–N movement from fields to rivers was provided by an inverse relationship between annual means for NO_3–N concentrations in soils and rivers. Because these losses can be avoided by delaying N applications, the practice of applying N several weeks or months before plants grow was linked to inefficient use of fertilizer and manure N by crops. Results of the study demonstrate how aggregate analyses of soil and cornstalk samples collected across many farms and years make it possible to identify the major factors affecting N management outcomes and, therefore, N management practices that are likely to produce the best outcomes within a watershed or region. This approach seems to have unique potential to interrelate the management practices of farmers, the efficiency of N fertilization, and NO_3–N concentrations in rivers.

Losses of NO_3–N from agricultural soils to rivers of the U.S. Corn Belt have recently been identified as a major cause of hypoxia in the Gulf of Mexico (Rabalais et al., 1996; Council for Agricultural Science and Technology, 1999; Turner and Rabalais, 1999; Alexander et al., 2000). This new problem adds to earlier concerns about environmental degradation caused by fertilizer and manure N that escapes from agricultural soils (Keller and Smith, 1967; Aldrich, 1980; Council for Agricultural Science and Technology, 1985; Hallberg, 1989; Power and Schepers, 1989). Nitrogen losses during corn production are of special concern because large areas are planted to this crop, N is applied at relatively high rates, and substantial amounts of NO_3–N are found in water that drains from these soils (Gast et al., 1978; Baker and Johnson, 1981; Cambardella et al., 1999; Jaynes et al., 1999, 2001). Studies have shown that much, often more than half, of the N applied is lost from fields by processes other than crop harvest during the first year after application (Allison, 1955; Blackmer, 1987; Sanchez and Blackmer, 1988; Cerrato and Blackmer, 1990; Timmons and Cruse, 1990).

Recent water quality studies on watershed scales (Schilling and Libra, 2000; Kalkhoff et al., 2000) clearly link high NO_3–N concentrations in Iowa rivers to row crop production, which primarily involves corn and soybean [*Glycine max* (L.) Merr.]. Although such studies confirm that row crop production is the primary NO_3–N source in rivers of this region, they do not help crop producers identify practices that reduce the problem. Crop producers often use soil and plant tissue tests to evaluate and improve N management practices on individual farms, but little attention has been given to the possible benefits of using these tools to evaluate and improve management practices on a watershed scale.

The terms "soil test" and "tissue test" are reserved for analyses that have been calibrated to indicate N sufficiency for plant growth. The Soil Science Society of America, for example, publishes one monograph for soil testing (Westerman, 1990) and another for soil analysis (Sparks et al., 1996). The tests are calibrated in field studies where several N rates are applied and grain yields are measured. A soil or tissue test is considered to be valid only after there is considerable experimental evidence of its ability to assess the N sufficiency for plant growth across a wide range of field conditions. The sufficiency of N for corn growth refers to the N supply relative to the crop needs, and the sufficiency of N is often described on numerical scales (i.e., test results) that range from below optimal to above optimal (Blackmer, 2000). The numerical scales are often divided into descriptive categories (e.g., "below optimal," "optimal," and "above optimal") to facilitate interpretation and to acknowledge that no single test value can be considered optimal for all conditions. The tests are diagnostic tools that use relationships observed in the past to estimate the sufficiency of N at any site where samples are collected.

A relatively new soil test for N in cornfields is based on NO_3–N concentrations in the surface 30-cm layer of soil when plants are 15 to 30 cm tall (Magdoff et al., 1984, 1990; Blackmer et al., 1989; Fox et al., 1989; Binford et al., 1992a; Meisinger et al., 1992; Morris et al., 1993; Sims et al., 1995; Schroder et al., 2000). This sampling time is late enough to reflect the effects of spring weather conditions and early enough to apply fertilizer if needed. As noted in a review by Bundy and Meisinger (1994), studies across a wide range of conditions show

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remarkable agreement that soil NO_3–N concentrations in the range of 20 to 25 mg N kg^{-1} indicate optimal N supplies for corn.

Traditionally, soil testing for NO_3–N has been done before fertilizer N is applied, but considerable work in Iowa has focused on testing soils after fertilizer N is applied (Blackmer et al., 1989; Binford et al., 1992a; Blackmer et al., 1997). Such testing enables evaluation of N fertilization practices, which can be described by considering application time, placement, N form, and application rate. The evaluation is based on ability to supply optimal amounts of N in late spring, when plants are entering the stage of rapid growth and N uptake. Interest in soil nitrate testing in Iowa originated from evidence that substantial amounts of the fertilizer N applied in the fall or early spring (i.e., the normal application times in Iowa) are often lost from the surface layer before plants are 15 cm tall (Blackmer et al., 1989).

A relatively new tissue test for measuring the sufficiency of N for corn is based on NO_3–N concentrations in the lower portions of cornstalks at the end of the season (Binford et al., 1990, 1992b; Hooker and Morris, 1999; Brouder et al., 2000; Fox et al., 2001). Studies across a wide range of conditions show that cornstalk NO_3–N concentrations greater than 0.75 g N kg^{-1} indicate that N supplies were sufficient for plant growth. The range of 0.25 to 2.0 g N kg^{-1} is considered to be an optimal range for producers in Iowa (Blackmer and Mallarino, 1996). Because this test is taken at the end of the growing season, it evaluates fertilization practices for their ability to supply optimal amounts of N for plant growth late in the season.

Our objective is to demonstrate how the new soil and tissue tests can be used to measure N sufficiency levels across many fields and how the results can be used to evaluate and improve management practices on the watershed scale. Analyses were conducted to identify the most important factors affecting the test values. This information was used to explain why some practices produced better outcomes than others and, therefore, to predict the effects of any change in management. An initial assumption was that the tests could be used to improve the efficiency of N management, where efficiency refers directly to amounts of N that must be applied to meet the needs of plants and indirectly to amounts of N lost from fields. This article focuses on how the tests can be used on the watershed scale and gives minimal attention to how the tests can be used on the individual-farm scale.

MATERIALS AND METHODS

More than 3200 soil and cornstalk samples were collected from Iowa cornfields during 8 of 12 consecutive years (Table 1). Both soil and cornstalk samples were usually collected at the same site (i.e., a 0.2-ha area representative of an important soil map unit within a field) within a year, but sampling of a site sometimes involved collecting either a soil or cornstalk sample. Two test areas representing different soil map units were usually sampled within each field studied.

Most samples (>90%) were collected within two major watersheds, the area upstream of Keosauqua on the Des Moines River and upstream of Wapello on the Iowa River. This area covers 68 700 km^2, about half of Iowa, and includes watersheds studied by Keeney and DeLuca (1993), Lucey and Goolsby (1993), Cambardella et al. (1999), and Kalkhoff et al. (2000).

The soil and cornstalk samples were collected in programs designed to help individual farmers evaluate and improve their N management. The methods for selecting farmers and fields differed slightly among years, but the fields were always selected before management outcomes were known. Unlike studies designed to characterize management practices within a region, random sampling is not necessary for studies designed to identify the major factors affecting N sufficiency levels attained under the range of conditions normally found in Iowa.

Soil samples were collected to a 30-cm depth when corn plants were 15 to 30 cm tall (usually within a week of 1 June) in accordance with guidelines for using the test in Iowa (Blackmer et al., 1997). Each sample was a composite of eight 3.2-cm-diameter cores in 1988, 1989, and 1991 and twenty-four 1.7-cm-diameter cores in 1996 to 1999. Cores for a sample were collected within a 0.2-ha area selected as relatively uniform and representative of a dominant soil map unit within the field. The samples were dried (49°C) within 48 h of collection and ground to pass a 2-mm sieve. Nitrate N was determined by KCl extraction and steam distillation (Keeney and Nelson, 1982) or flow-injection analysis (Lachat Instruments, Milwaukee, WI).

Cornstalk samples were collected 1 to 3 wk after physiological maturity (mid-September to mid-October) by cutting a 20-cm segment of stalk beginning 15 cm above the ground from each of 15 plants in accordance with guidelines for using this test in Iowa (Blackmer and Mallarino, 1996). The samples were dried at 60°C and ground to pass a 0.5-mm sieve. Subsamples were shaken in 0.025 M $Al_2(SO_4)_3$ for 30 min and filtered. Nitrate N in the filtrates was determined by ion-specific electrode after adding 1 mL of 2 M $(NH_4)_2SO_4$ to each 50 mL of filtrate to minimize differences in ionic strength.

Information provided by farmers indicated that about a quarter of the samples (soil plus cornstalk) were from fields that received all fertilizer N as fall-applied anhydrous ammonia. The mean application rate was 164 kg N ha^{-1} for these

Table 1. Numbers of soil and cornstalk samples collected to assess N sufficiency levels in Iowa cornfields.

Year	Number of soil samples†		Number of cornstalk samples†	
	Without manure	With manure	Without manure	With manure
1988	101 (184)	70 (150)	97 (184)	59 (153)
1989	95 (165)	84 (155)	77 (161)	74 (152)
1991	81 (147)	37 (110)	81 (147)	37 (110)
1995	0	0	140 (139)	66 (113)
1996	93 (122)	67 (124)	342 (143)	116 (143)
1997	177 (118)	63 (87)	128 (143)	29 (85)
1998	232 (149)	63 (134)	36 (151)	8 (178)
1999	341 (155)	49 (164)	331 (156)	41 (157)

† Numbers in parentheses are mean N rates (kg ha^{-1}) that farmers applied as commercial fertilizer.

Table 2. Summary of soil NO_3–N concentrations found in 1553 samples collected to assess N sufficiency levels in Iowa cornfields.

Year	Mean NO_3–N concentration in soil†		Percentage of samples with <10 mg NO_3–N kg^{-1}	
	Without manure	With manure	Without manure	With manure
	mg NO_3–N kg^{-1}		%	
1988	42 (21)	41 (16)	0	0
1989	44 (22)	53 (27)	0	4
1991	23 (15)	23 (13)	21	16
1996	21 (14)	27 (17)	18	16
1997	30 (22)	35 (24)	10	3
1998	18 (17)	27 (23)	41	24
1999	16 (9)	21 (11)	27	16

† Numbers in parentheses are standard deviations.

fields. Another quarter of the samples were from fields that received all fertilizer N in the spring before planting, which usually occurred in the second half of April. The fertilizer usually was anhydrous ammonia or a urea–ammonium–nitrate solution, and the mean application rate was 146 kg N ha^{-1}. The remaining half of the samples were collected from fields that received a combination of fall- and spring-applied N. The mean combined application rate was 153 kg N ha^{-1}. Commercial fertilizer was applied in the fall at rates >100 kg N ha^{-1} at 36% of the sites sampled.

Information provided by farmers indicated that animal manure had been applied for the cropping year studied at 30% of the areas sampled. Liquid manure from modern swine (*Sus scrofa*) production units was applied at 27% of the manured sites at a mean reported rate of 37 kL ha^{-1}. Beef cattle (*Bos taurus*) manure was applied at 21% of the manured sites at a mean reported rate of 23 Mg ha^{-1}. Most of the remaining 52% of the manured sites received two or more manure types or the manure type was not reported. Information concerning manure applications for previous cropping seasons was not collected, but fields that receive manure usually receive applications every other year. All information concerning manure composition and application rates has great uncertainty, but it seems that most farmers selected application rates to supply about 150 kg N ha^{-1} for plant growth in accordance with current recommendations (Killorn and Lorimor, 1999).

Other farming practices were generally representative of those found in Iowa. The previous crop was soybean in 60% of the fields, corn in 25% of the fields, and alfalfa (*Medicago sativa* L.), oat (*Avena sativa* L.), or wheat (*Triticum aestivum* L.) in the remaining 15% of the fields. Tillage for about half of the fields involved chisel plowing, disking, and field cultivating before planting. Management at the remaining sites was divided between moldboard plowing, ridge tillage, strip tillage, and no tillage.

Statewide monthly precipitation data for each year as well as 30-yr means for monthly precipitation data were obtained for Iowa from the National Climatic Data Center (2002). Rainfall data from >190 stations were included in each monthly mean. Information concerning water flows in the Des Moines River at Keosauqua and the Iowa River at Wapello were obtained from the United States Geological Survey (2002a). Information concerning amounts of NO_3–N carried by the Iowa River at Wapello were also obtained from the United States Geological Survey (2002b).

Statistical analyses were used to assess the relative importance of various factors affecting soil and stalk NO_3–N concentrations. The analyses involved models that considered the variables "year," "manure," and "fertilizer N rate" and linear and quadratic interactions of these variables by using the SAS generalized linear model procedure (SAS Institute, 1996). "Year" and "manure" were considered categorical variables, and "fertilizer N rate" was considered a continuous variable. "Manure" was considered a categorical variable because there was uncertainty concerning rates of manure N applied.

RESULTS

Soil and Cornstalk Nitrate Concentrations

Annual means for NO_3–N concentrations in the surface 30-cm soil layers ranged from 16 to 44 mg N kg^{-1} at sites without animal manure and 21 to 53 mg N kg^{-1} at sites with animal manure (Table 2). Variation among these means seems relatively large because optimal NO_3–N concentrations usually are considered to be 20 to 25 mg N kg^{-1} (Bundy and Meisinger, 1994). The proportions of samples having very low NO_3–N concentrations (i.e., <10 mg N kg^{-1}) also illustrate high variation among years. These ranged from 0 to 41% for sites without animal manure and 0 to 24% for sites with animal manure (Table 2). These values indicate substantial differences among years in amounts of NO_3–N in soils just before plants began rapid growth in June.

Annual means for NO_3–N concentrations in cornstalks at the end of the season ranged from 1.1 to 7.3 g N kg^{-1} for sites without animal manure and 2.1 to 7.8 g N kg^{-1} for sites with animal manure (Table 3). De-

Table 3. Summary of cornstalk NO_3–N concentrations found in 1662 samples collected to assess N sufficiency levels in Iowa cornfields.

Year	Mean concentration of cornstalk NO_3–N†		Percentage of samples with <0.25 g NO_3–N kg^{-1}	
	Without manure	With manure	Without manure	With manure
	g NO_3–N kg^{-1}		%	
1988	4.6 (2.6)	5.1 (3.3)	1	0
1989	7.3 (3.6)	7.8 (3.0)	5	0
1991	2.6 (2.9)	2.8 (3.2)	26	35
1995	1.1 (1.2)	2.4 (2.4)	30	17
1996	2.2 (2.1)	3.2 (2.6)	16	16
1997	2.2 (2.0)	2.1 (1.8)	13	21
1998	1.1 (1.3)	2.1 (2.9)	47	38
1999	1.5 (1.9)	2.2 (2.5)	38	34

† Numbers in parentheses are standard deviations.

pending on year, from 1 to 47% of the samples from sites without animal manure and from 0 to 38% of the samples from sites with animal manure had below-optimal NO_3–N concentrations (<0.25 g N kg^{-1}). Because NO_3–N concentrations in cornstalks provide a direct measure of N sufficiency for plant growth during the second half of the growing season, these measurements provide direct evidence that sufficiency of N for plant growth varied greatly among years.

Factors Affecting Nitrate Test Values

Statistical models that considered the variables "year," "manure," and "fertilizer N rate" and interactions of these variables explained 37% of the variation (i.e., model R^2 = 0.37) in soil NO_3–N concentrations and 43% of the variation in cornstalk NO_3–N concentrations (P = <0.0001 for both models). The most important variables accounting for explained variation in soil NO_3–N concentrations were year (81%), manure (4%), fertilizer N rate (5%), and a year by fertilizer N rate interaction (8%). The most important variables accounting for explained variation in cornstalk NO_3–N concentrations were year (89%), manure (3%), fertilizer N rate (4%), and a year by fertilizer N rate interaction (3%). Although the variable "year" accounted for most of the variation explained by both models, these analyses do not indicate the specific factors responsible for observed differences among years.

We did not anticipate that the variable year would explain most of the variability in soil and cornstalk NO_3–N concentrations. This finding is reasonable, however, if it is recognized that most farmers in Iowa tend to apply somewhat similar N rates as fertilizer or animal manure and that our study included a wide range of specific factors (i.e., rainfall, temperature, evaporative demand for water, etc.) in the variable year. The results suggest that prevailing ideas concerning the relative importance of factors affecting variability in N supplies in cornfields may be skewed by studies that include several N application rates while holding other factors constant.

Rainfall Effects

The variable "year" accounted for much of the variation in soil and cornstalk NO_3–N concentrations, but the statistical models did not indicate the specific factors responsible for differences among years. No single factor should be expected to explain all the variation included in years. We found that 74% of the year-to-year variation in annual means for soil NO_3–N concentrations (Fig. 1A) could be explained by considering state means for rainfall early in the cropping season (i.e., March through May). Rainfall before March should not be expected to have much effect on soil test NO_3–N because the water tends to run off frozen soils. Rainfall after May could have little influence on mean soil test NO_3–N values because soils were sampled in the first half of June. Rainfall is known to promote NO_3–N losses from soils by leaching and denitrification, so it is reasonable to conclude that early-season rainfall promoted NO_3–N losses from the layer of soil sampled.

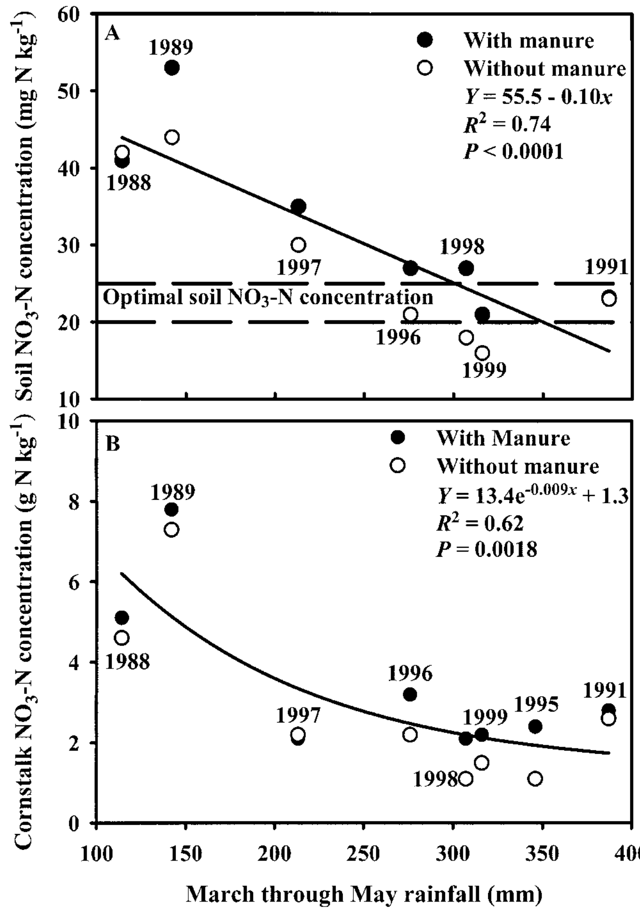

Fig. 1. Relationships between early-season rainfall and (*A*) annual means for soil NO_3–N concentrations measured in early June and (*B*) annual means of stalk NO_3–N concentrations measured at the end of the season.

Evidence that early-season rainfall promoted N losses from the rooting zone of corn is provided in Fig. 1B, which shows that this rainfall explained 62% of the year-to-year variation in mean cornstalk NO_3–N concentrations. This relationship is curved because NO_3–N concentrations in cornstalks are not linearly related to N supplies in soils (Binford et al., 1990, 1992b). The trend observed in Fig. 1B indicates that the amounts of N found by the corn plants decreased as amounts of early-season rainfall increased. Data from the cornstalk test are derived from different measurements than the soil test, so they provide independent support for the conclusion that early-season rainfall promoted NO_3–N losses from the cornfields.

Differences between the relatively wet and relatively dry springs are illustrated in Fig. 2, which compares monthly means for rainfall over the past 30 yr with the means for 1991 and 1999 (wet years) and the means for 1988 and 1989 (dry years). Rainfall normally exceeds evapotranspiration only in the winter and spring in Iowa (Nelson and Uhland, 1955; Stanford, 1982). The observed importance of early-season rainfall on soil NO_3–N concentrations, therefore, is reasonable because substantial amounts of water move downward through soil profiles when spring rainfall is significantly above

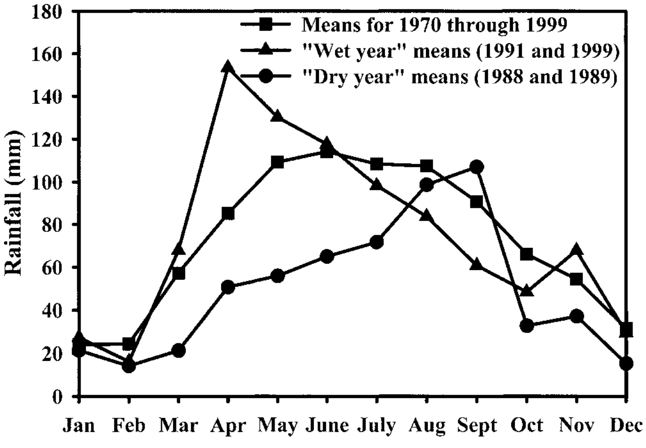

Fig. 2. Mean monthly rainfall for the two wettest years (1991 and 1999), the two driest years (1988 and 1989), and 30-yr means for rainfall in Iowa.

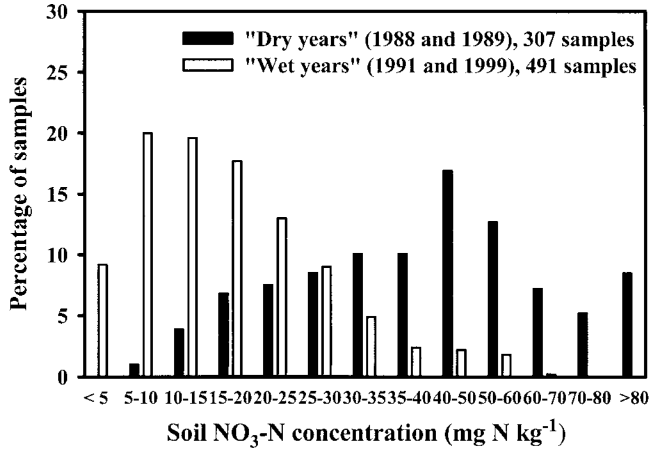

Fig. 3. Distributions of soil NO_3–N concentrations in relatively wet and dry years.

normal whereas little water movement through the soil profile occurs when rainfall is significantly below normal. Subsurface drainage is extensively used to remove excess water from soils of this region (Gast et al., 1978; Baker and Johnson, 1981; Cambardella et al., 1999; Jaynes et al., 1999, 2001) and little water flows through these drains during relatively dry years.

The relationships in Fig. 1 are useful because they illustrate the average effects of the most important measured factor (early-season rainfall) affecting sufficiency of N for plant growth across the range of conditions studied. In addition to the average effects of one factor, however, information concerning the expected distributions of test values is also needed for effective evaluations of N management practices. The use of soil and tissue testing in survey-type sampling schemes on the watershed scale can generate enough observations to characterize these distributions. The distributions of test values shown in Fig. 3 and 4, for example, illustrate the effects of the most important factor identified (i.e., early-season rainfall) relative to the importance of *all* other factors operative in the fields studied. This presentation of data emphasizes the importance of additional factors and the need for efforts to identify these factors. The distributions of test values observed in surveys of many fields and years need to be clearly distinguished from the distribution of test values observed in conventional small-plot experiments. Such experiments give biased estimates of the relative importance of various factors affecting test values because variation due to selected factors is enhanced by addition of treatments, whereas variation due to all other factors is suppressed by generally accepted experimental techniques.

The observed variability in test results within years could be due to spatial variability in rainfall as well as variability in soil characteristics and management practices, including N application rates. Inadequate data were collected to explore the possibility that field-scale rainfall measurements would have explained more variability than did regional means for rainfall.

Water Flow in Rivers

We found that 79% of the year-to-year variation in annual means for soil NO_3–N concentrations could be related to annual mean water flow through the two main river systems draining the central portion of Iowa (Fig. 5). Means for river flow during March through May explained 91% of the variation in cornstalk NO_3–N concentrations (Fig. 6). Such relationships are reasonable because both test values and river flows were influenced by rainfall. Relationships between test values and river flows are important because they provide independent evidence (i.e., not based on rainfall measurements) that the sufficiency of N for plant growth is related to the water amounts that move from fields to rivers before plants grow. Although it is generally recognized that above-average rainfall results in above-average N losses from fields, relationships between measured N losses from fields and river flows have received relatively little attention.

Annual means for spring soil NO_3–N concentrations (Fig. 7A) and end-of-season cornstalk NO_3–N concentrations (Fig. 7B) were inversely related to annual means

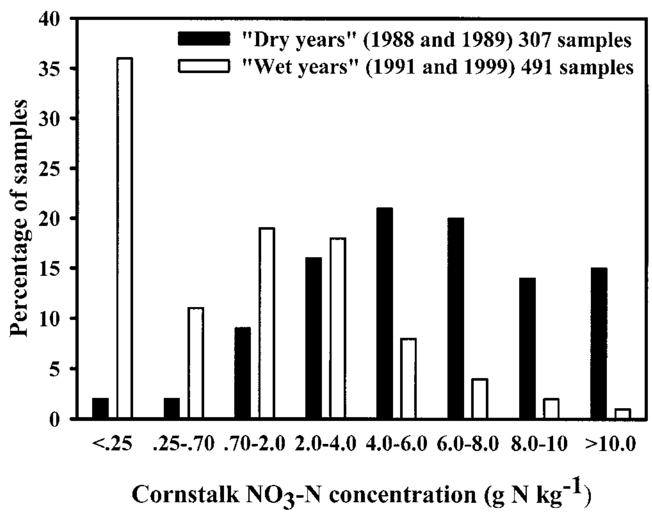

Fig. 4. Distributions of cornstalk NO_3–N concentrations in relatively wet and dry years.

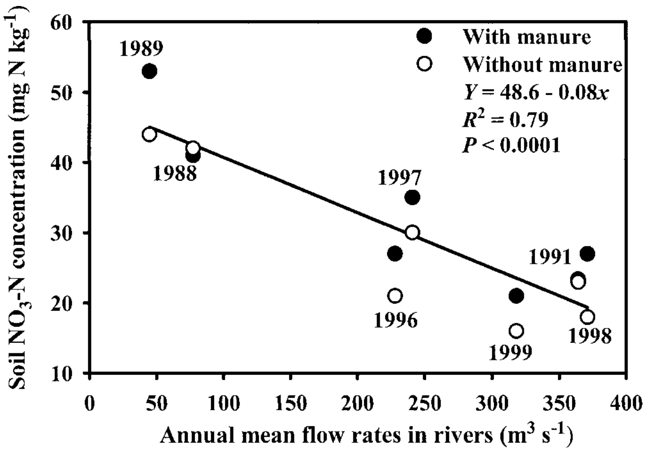

Fig. 5. Relationship between annual means for soil NO_3–N concentrations in early June and annual means for flow in the Des Moines and Iowa Rivers.

for NO_3–N loads carried by the Iowa River at Wapello. Comparable NO_3–N data could not be found for the Des Moines River. These observations show that the disappearance of NO_3–N from watershed soil was accompanied by an increase in amounts of NO_3–N transported in the watershed river.

Earlier studies have shown that NO_3–N concentrations in rivers tend to be greatest in the spring and that annual means for NO_3–N concentrations tend to increase with mean annual water flows in these rivers (Keeney and DeLuca, 1993; Lucey and Goolsby, 1993; Kalkhoff et al., 2000). Such trends indicate that more rainfall tends to tap additional NO_3–N sources rather than to merely dilute NO_3–N from the same sources. Our observations add to the earlier studies by directly interrelating early-season rainfall, increased NO_3–N loads in rivers, and measured decreases in NO_3–N supplies for plant growth in the associated agricultural soils.

Fertilizer Effects

We found that soil (Fig. 8A) and cornstalk (Fig. 8B) NO_3–N concentrations tended to increase with increases

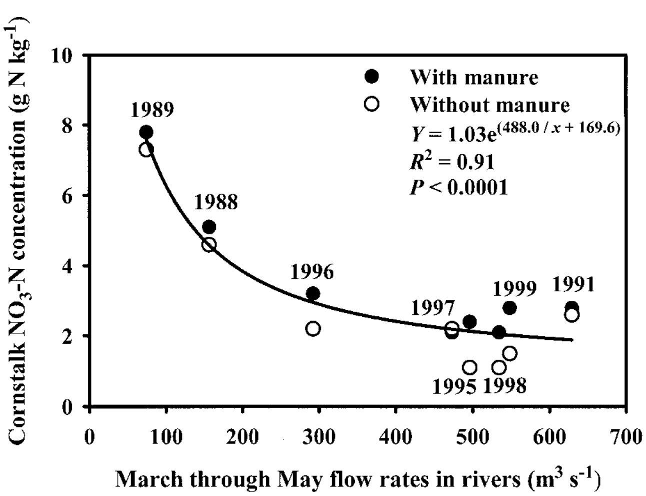

Fig. 6. Relationship between early-season water flows in the Des Moines and Iowa Rivers and annual means of cornstalk NO_3–N concentrations measured at the end of the season.

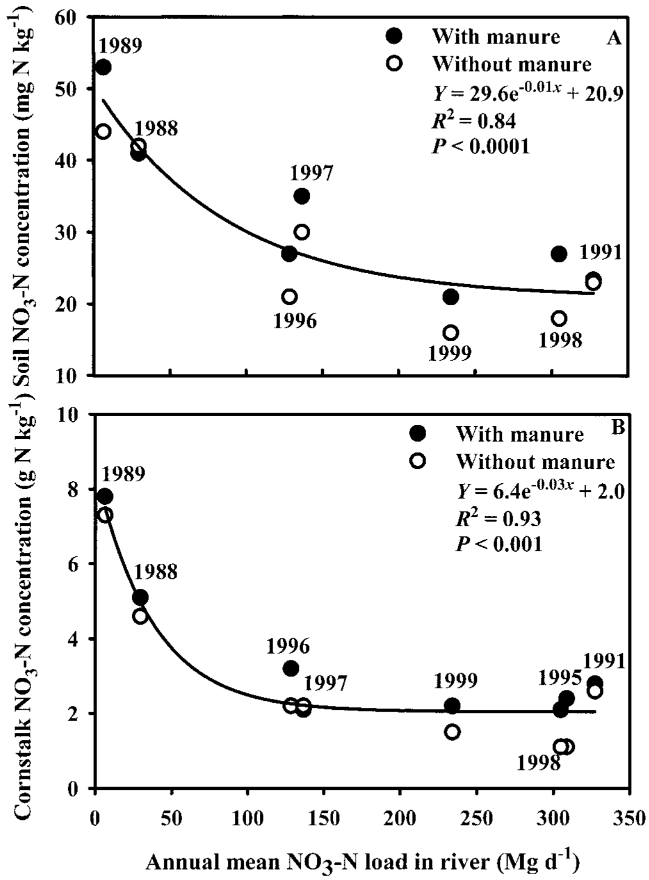

Fig. 7. Relationships between annual mean NO_3–N loads in the Iowa River at Wapello and annual means for (*A*) soil NO_3–N concentrations in late spring and (*B*) cornstalk NO_3–N concentrations at the end of the growing season.

in fertilizer N rates applied by farmers. Data are presented as means for N-rate categories to illustrate the average effects on test values with minimal interference from other factors. This averaging across other factors is necessary because, as indicated earlier, statistical analyses showed that fertilization rates explained only a small portion of the variation in test values. Separate analyses indicated that relationships between N fertilization rates and concentrations of soil and cornstalk NO_3–N were significant ($P < 0.05$) only in about half of the years studied (data not shown). These observations are consistent with the statistical analyses showing that part of the variation in soil and cornstalk NO_3–N concentrations was explained by an interaction of the variables "year" and "fertilizer N rate."

The effects of N fertilization rates in this study should not be confused with the expected effects of N rates in trials where all other factors are held constant. Higher fertilization rates should be expected to result in higher cornstalk NO_3–N concentrations in such trials. However, higher fertilization rates should not be expected to result in higher cornstalk NO_3–N concentrations in situations where fertilizer application rates were correctly selected to complement other N sources and thereby provide optimal N supplies for plant growth. The relationships between fertilization rates and N suffi-

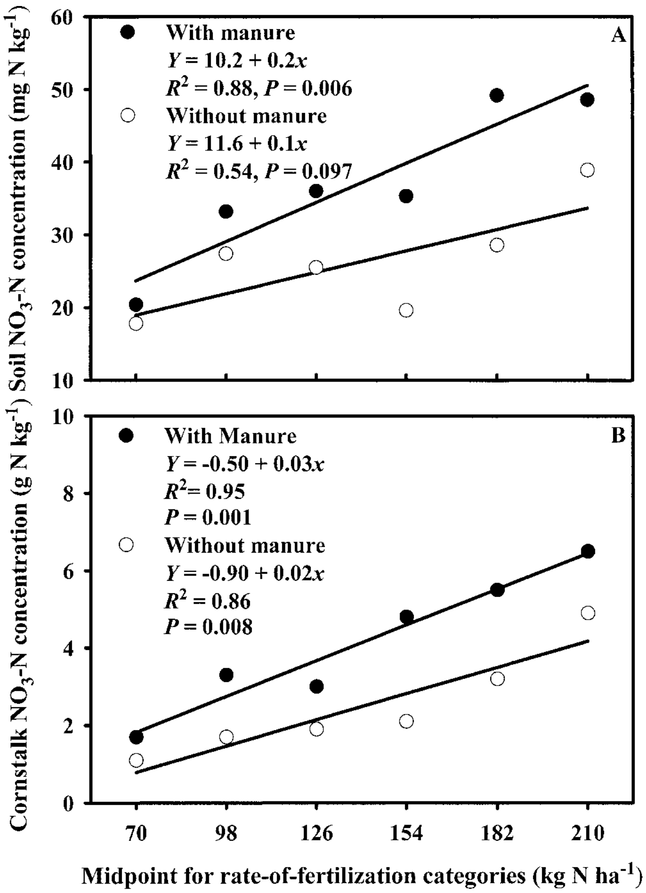

Fig. 8. Mean (*A*) soil and (*B*) cornstalk NO_3–N concentrations for six rate-of-N-fertilization categories for soils with and without animal manure.

ciency levels observed in this study, therefore, indicate that fertilization rates were not correctly adjusted to address the major factors affecting N sufficiency levels in the fields surveyed. This is not surprising because early-season rainfall has not been recognized as an important factor affecting N fertilizer needs for corn (Peterson and Voss, 1984; Midwest Planning Service Livestock Waste Subcommittee, 1985; Oberle and Keeney, 1990; USDA Natural Resources Conservation Service, 1999).

The mean reported rate of N fertilization (always applied before soil sampling) was 137 kg N ha^{-1} for manured soils and 150 kg N ha^{-1} for soils that did not receive animal manures. A difference in rate should be expected because farmers have long been advised to give credit for N in animal manure when selecting N fertilization rates (Midwest Planning Service Livestock Waste Subcommittee, 1985; Killorn and Lorimor, 1999; USDA Natural Resources Conservation Service, 1999). The observed mean difference in fertilization rate (15 kg N ha^{-1}), however, is much smaller than would occur if farmers believed that the manure application rates were high enough to supply adequate N for crop growth. The relatively small credit for N in animal manures is consistent with the results of surveys of farming practices (Duffy and White, 1998; Nowak et al., 1998), which show that most farmers make little or no downward adjustment in fertilization rates to account for N applied as animal manure.

Manure Effects

Statistical analyses presented earlier indicated that animal manure applications explained relatively small portions of the total observed variation in soil and cornstalk NO_3–N concentrations. Evidence that manure increased the test values is presented in Fig. 1, 5, 6, 7, and 8, which distinguish between sites with and without manure. Figures 8A and 8B are most informative because they show the effects of manure relative to fertilizer after the effects of early-season rainfall and other factors associated with year were removed by averaging across years.

The regression lines in Fig. 8A predict soil NO_3–N concentrations of 27 and 40 mg N kg^{-1} without and with animal manure when fertilizer is applied at a rate of 150 kg N ha^{-1}, which is generally representative of rates that most producers apply. The difference between these values (13 mg N kg^{-1}) represents the average contribution of animal manure. The soil NO_3–N concentrations include about 10 mg N kg^{-1} that would be in the soil if no fertilizer or manure had been applied (Blackmer et al., 1989; Binford et al., 1992a). If this background concentration is subtracted, the average effect of fertilizer can be estimated at 17 mg N kg^{-1} (27 minus 10 mg N kg^{-1}). Although there is considerable uncertainty in any estimate associated with the manure, it seems that manure had a slightly smaller average effect on N supply for plant growth than did fertilizer N. Data generated by the end-of-season test for cornstalk NO_3–N support this conclusion (Fig. 8B). These findings should be expected where manure is usually applied at recommended rates, which are intended to supply adequate but not excessive amounts of N for plant growth.

A major point illustrated in Fig. 8 is that the effects of fertilizer and manure are additive. Above-optimal N supplies, therefore, should be associated with failure to lower fertilizer N rates after manure applications rather than to the actual manure application. Our results do not challenge the popular idea that manure is often applied at rates that supply excess N and thereby pose a serious threat to water quality (Power and Schepers, 1989; Sharpley et al., 1998; Jackson et al., 2000; USEPA, 2001). However, they clearly suggest that the relationships between management practices in fields and NO_3–N concentrations in rivers would be easier to understand if more attention were given to the fertilizer N rates applied to soils that receive animal manure.

DISCUSSION

Early-Season Nitrogen Losses from Fields to Rivers

The observed relationships between early-season rainfall and soil test values in late spring provide evidence that this rainfall often induced substantial NO_3–N losses from soils before plants grew. Additional and independent evidence for early-season NO_3–N losses is provided by the observed relationships between early-season rainfall and sufficiency of N for corn growth as indicated by the end-of-season test for cornstalk NO_3–N. Supporting evidence is also provided by the finding of a relationship between early-season NO_3–N losses from soils and amounts of NO_3–N carried by the associated rivers. Collectively, these observations provide compelling evidence that early-season NO_3–N losses from soils are an important factor affecting N supplies for plant growth and NO_3–N concentrations in rivers.

Abundant spring rainfall clearly is the direct cause of the NO_3–N losses from fields, but application of fertilizer N and animal manure weeks to months before crops grow should be recognized as a management practice that accentuates this important effect of rainfall. Although rainfall cannot be controlled, the fertilization time can be delayed to prevent early-season N losses. The findings of this study, therefore, are consistent with earlier reports emphasizing need to synchronize N applications with periods of plant growth (Ferguson et al., 1991; Jokela and Randall, 1989; National Research Council, 1993).

Delaying N applications to minimize rainfall-induced NO_3–N losses before plants grow should be expected to reduce average N fertilization rates for two different reasons. The first is the obvious reduction in rate to compensate for the average reduction in N loss. The second is an additional decrease in rate due to a reduction in uncertainty in estimates of fertilizer need. Recommended fertilization rates normally include some extra N that is added as insurance to address economic risk that occurs because fertilizer must be applied before crops are grown (Barber, 1973; Babcock, 1992). Reductions in uncertainty caused by early-season rainfall should reduce amounts of "insurance N" included in estimates of fertilizer need. The methods described in this paper, therefore, essentially help farmers to identify ways to improve the efficiency of N fertilization. This increase in efficiency has the potential to increase profits for farmers while minimizing N losses to rivers.

Evaluating Management Outcomes

The information acquired by using the soil NO_3–N test after fertilizers are applied needs to be clearly distinguished from that acquired by testing soils before fertilizers are applied. Soil testing after fertilization evaluates an outcome of management (i.e., sufficiency of N when plants start rapid growth), whereas soil testing before fertilization estimates the amounts of N that should be applied. Soil testing after fertilization can detect problems associated with N losses soon after fertilization whereas soil testing before fertilization cannot detect these problems.

The cornstalk test for NO_3–N evaluates the sufficiency of N at the end of the growing season, which is an important management outcome. Like yield measurements at the end of the season, the results are influenced by all the important factors occurring during the season. Results of the cornstalk test are more useful when evaluating N management practices, however, because the effects of N are separated from other factors that influence final yields.

Observations during the past decade clearly indicate that most corn producers believe that they are not responsible for high NO_3–N concentrations in rivers because they are following practices that are described as "best management practices." Most producers are surprised to learn, therefore, that the tests frequently indicate that N supplies are significantly above or below optimal when these practices are followed. Such observations suggest that management guidelines given to farmers may be a critical barrier to improving N management. A noteworthy advantage of the methods described in this paper is the ability to objectively assess problems in guidelines for N management as well as problems caused by producers who do not follow these guidelines.

CONCLUSIONS

The late-spring test for soil NO_3–N and the end-of-season test for cornstalk NO_3–N offer a novel way to help crop producers join in efforts to reduce NO_3–N losses from fields to rivers. When used to evaluate N management outcomes, these tools provide an efficient way to evaluate and improve N management practices used in a region or watershed. The results of a few samples give site-specific feedback useful to individual farmers. Aggregate analyses of results from large numbers of samples collected across many sites and years make it possible to identify the major factors affecting management outcomes and the management practices that are most likely to produce the best outcomes within a region. This use of the tests can reveal the natural relationships among management practices of individual corn producers, the efficiency of specific N fertilization practices, and NO_3–N concentrations in rivers.

Early-season rainfall and the associated N losses from Iowa cornfields was identified as the most important factor affecting variation in the sufficiency of N for plant growth across the range of conditions studied. This finding is important because it means that delaying and reducing fertilization rates should increase profits for farmers more than is generally recognized. This finding indicates need to reevaluate the effects of guidelines suggesting that it makes little difference when fertilizers and manures are applied.

Many farmers are decreasing their profits by purchasing and applying unneeded commercial fertilizer N to fields already treated with animal manure. It seems likely, therefore, that most farmers would welcome watershed-scale programs that use the soil and tissue tests to measure the outcomes of fertilizer and manure applications and thereby objectively evaluate and improve N recommendations and management practices.

The major findings of this study may not apply to regions with different climates or cropping systems. The methods used, however, should be of interest in any region where there is concern about the effects of row crop production on NO_3–N concentrations in rivers.

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